U.S. Department
of Transportation

Federal Aviation
Administration

Advisory Circular

Subject: INSTALLATION OF TURBOCHARGERS IN SMALL AIRPLANES WITH RECIPROCATING ENGINES

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Change:

1. PURPOSE. This advisory circular (AC) provides information and guidance concerning an acceptable means, but not the only means, of showing compliance with Part 23 of the Federal Aviation Regulations (FAR), applicable to approval procedures and installation of turbochargers in small airplanes. Accordingly, this material is neither mandatory nor regulatory in nature and does not constitute a regulation.

2. RELATED FAR SECTIONS. Section 23.909 and applicable sections of Part 33 of the FAR (Part 3 of the Civil Air Regulations (CAR) does not have a corresponding requirement).

3. BACKGROUND.

a. Exhaust gas-driven turbochargers are available for use with reciprocating engines to:

(1) Increase takeoff and maximum continuous power available at sea level and altitude (turbosupercharged - boosted).

(2) Maintain maximum continuous or cruise powers above sea level altitude (turbonormalized).

(3) Provide a source of air to pressurize the cabin.

NOTE: The word turbocharger will be used throughout this AC to include both turbosupercharged boosted and turbonormalized engines.

b. Section 23.909 contains requirements for approval of turbochargers on small airplanes. This regulation refers to design standards required in Part 33 of the FAR. Part 3 of the CAR does not specifically cover the approval requirements for the installation of a turbocharged engine in an airplane.

c. The applicant is expected to substantiate, through suitable engineering investigations and/or tests, that the turbocharged engine installation complies with the applicable airworthiness requirement for the airplane in which the installation is made. The turbocharger should be approved as part of the engine; however, the engine turbocharger may be approved under the provisions of § 23.909(a). The turbocharger approval of the engine installation is included in the provisions of § 23.909(b) and (c).

4. DEFINITIONS. The following definitions apply to this AC:

a. Turbocharger - Any exhaust gas-driven device that is added to or part of a reciprocating engine. This definition applies to:

(1) Engines turbonormalized having a turbocharger that maintains approximately sea level manifold pressure to a critical altitude.

(2) Engines turbosupercharged having a turbocharger that provides a manifold pressure greater than normally aspirated sea level conditions and maintains this pressure to a critical altitude.

(3) Pressurization systems utilizing air provided by a turbocharger.

b. Engine supercharged - Any engine having a mechanical aircharging device (compressor) that provides a manifold pressure equal or greater than for normally aspirated sea level conditions and maintains this manifold pressure to a critical altitude.

c. Intercooler - Any device installed in the engine induction air system at the exit of turbocharger or supercharger compressor intended to reduce the temperature of air compressed by the turbocharger.

5. DISCUSSION.

a. The addition of a turbocharger to an engine may be expected to have varied effects on the reliability and power output of the engine. It should first be established that the engine will tolerate being turbocharged. Qualifications of the proposed turbocharger should also be established. The increased complexity of the combination necessitates a thorough investigation be conducted to determine compliance with Part 33. Engineering programs for substantiating the acceptability of these engines should consider the following items:

(1) The detonation margin of reciprocating airplane engines at various power settings is related primarily to carburetor or induction air inlet temperature and pressure, engine exhaust back pressure, ignition timing, fuel grade, fuel flow, carburetor or injector metering characteristics, compression ratio, and cooling. Other features, such as cylinder combustion chamber design, induction system design, and fuel/air distribution, are also involved to a lesser degree. With the exception of fuel/air distribution, such features may not be changed when a turbocharger is installed. The addition of the turbocharger to an engine not specifically designed for it may affect carburetor inlet and induction air temperature to appreciably reduce the detonation margin. If the original margin is small, unsatisfactory detonation characteristics may result. Turbocharging is more easily accomplished on low compression ratio engines than on high compression ratio engines.

(2) Induction air temperature may become critical at altitude because of the increased compression of air required. The turbocharger speed will also increase with altitude because increased turbine wheel speed is necessary to achieve the required higher pressure ratio to maintain manifold pressure. If detonation characteristics are unsatisfactory, it is probable that changes of one

or more of the other primary factors may be necessary to restore detonation margins. The effects of these changes should also be evaluated in other related areas. Changes or adverse affects such as compression ratio, ignition timing, and fuel metering performance and endurance may require recertification of the engine.

(3) The matching of the turbocharger and engine thermodynamic characteristics interrelate so many factors that prediction of the power characteristics of this combination does not readily lend itself to the theoretical approach. It may be possible to combine test data and analysis to arrive at the performance and correction factors for the combination. Simulated or actual altitude testing, as well as ground testing, may be necessary in this approach. The availability of torque meters for small reciprocating engines makes the actual altitude test approach possible. This permits use of the airplane as a test bed which may be desirable to some original manufacturers and modifiers.

(4) Turbochargers currently in use require oil lubrication from an external source. If pressurized engine oil is utilized, the additional oil required may exceed the capacity of the engine oil pump at high oil temperatures or when the pump and bearing clearance approach service limits. The turbocharger rejects heat to the oil increasing the load on engine oil cooling provisions and may exceed oil system capacity; therefore, evaluations should be conducted under hot day conditions at the most severe operating limits. If hot day conditions are not available, the observed temperatures may be corrected for hot day conditions.

(5) Some air is normally contained in turbocharger scavenge oil. If not removed by an oil separator, this increases the burden on the engine breather system. If scavenged by the engine scavenge system, it may overload this system. These possibilities should be considered.

(6) If it is not possible to locate the turbocharger such that the turbocharger lubricating oil is scavenged by gravity and/or the engine scavenging pump is inadequate to handle this oil, an additional or increased capacity engine driven scavenge pump may be necessary.

(7) If a separate turbocharger lubricating system is used, the oil tank pressure and scavenging pumps, oil lines, and fittings should be evaluated for a satisfactory system.

(8) Cold oil operational characteristics of all turbocharger exhaust wastegate and any oil operated flow control devices should be considered early in the design phase of the overall installation.

(9) Past investigation and substantiation of endurance and reliability characteristics of the unsupercharged engine may not be completely applicable because of changes to parts, fuel flow metering, or ignition specifications and revisions to limitations to achieve necessary or desirable detonation or power characteristics. Each change should be considered in light of previous substantiation, service experience on the engine or similar engines, and the new operating conditions imposed. The ability of the engine and turbocharger to meet the standards established by test under subpart B of Part 33 should be demonstrated. Compliance of other components with the standards established by

§§ 33.49 and 33.53 should be substantiated by tests, service experience, engineering analysis, or combinations of these methods. Identification of the turbocharger should be controlled by top assembly part number and not model number alone.

(10) The effect of higher average horsepower output and cycle of the turbocharged engine makes any manufacturer recommended overhaul periods established for nonturbocharged operation inapplicable. The new recommended overhaul periods should be reestablished at a time interval to provide an acceptable reliability level.

(11) The possible damage from turbine or compressor wheel burst necessitates investigation of the integrity of these components or demonstration of their containment within their respective housing (case).

(12) Each engine installation should be investigated to establish compliance with speed and turbine inlet temperature limits of the turbocharger. Actual or simulated altitude investigations may be necessary to establish the critical conditions for overtemperature and overspeed. Compressor pressure ratio, airflow, and inlet temperature, are significant factors in determining the turbocharger speed. The maximum speed cannot adequately be established by only relating these variables to the manufacturer's map for a specific turbocharger. An example is the significant change in turbocharger speed for the same manifold pressure at various engine speeds which affect airflow. It is, for this reason, that turbocharger speed should be measured in the airplane during flight tests, for each manifold pressure and engine RPM setting. Above the critical altitude, available manifold pressure drops off and the manifold pressure vs. altitude is usually specified in the form of a limitation curve or chart tabulation. Mixture fuel-air ratio and inlet temperature are the dominant factors controlling exhaust gas temperature. Measurement of exhaust gas (turbine inlet) temperature under simulated or actual hot day operation to critical altitude will verify maximum turbocharger inlet temperature. Proper selection of turbocharger materials is essential in establishing maximum permitted operating temperature, particularly at cruise RPM.

(13) If an intercooler is used, the mounting provision on the engine should be adequate to withstand the loads imposed on the system. Also, any changes to the engine approved limits and operating procedures should be established including means to monitor the limits. Installation of an intercooler is likely to significantly affect engine horsepower output with the same manifold pressure and RPM; therefore, an accurate method of limiting engine horsepower is necessary.

(14) Each engine installation should be investigated to ensure freedom from compressor surge at all operating points. Consideration of low airflow (at low engine RPM cruise) and higher pressure ratio (altitude and manifold pressure) should particularly be investigated.

b. The addition of a turbocharger to an engine installation may be expected to have varied effects on the reliability of the installation. The induction system will experience higher temperatures due to the heat generated in compressing induction air, and will experience positive internal pressure instead of suction by the engine. The exhaust system will experience higher flow rates of hot exhaust gas, increasing the temperature of the metal in the exhaust ducts, and increasing internal pressure. These changes necessitate a thorough investigation be conducted to determine compliance with Part 23. Engineering programs for substantiating these installations should consider the following:

(1) The pressurization of the exhaust system increases the importance of durability of the exhaust system components. Failure of the system results in a reduction of engine performance and increases the danger of fire due to escaping hot gases in the 1500° to 1600°F temperature range. Occasionally, exhaust gas temperature extremes of 1800°F may be reached and could serve as sources of ignition of flammable fluids and damage to lines, controls, and structure. Radiant energy from the hot surfaces may be sufficient to damage other components which may be in close proximity. Requirements for protection in this area are based on these considerations.

(2) The turbocharged engine's ability to produce more horsepower at altitude together with the decreased density of the cooling air at altitude results in a lower ratio of cooling air to horsepower effect at altitude than at sea level. Although some benefit can be gained from lower cooling air temperature at altitude, it is overshadowed by decreased cooling air density, and higher available power output. Therefore, installation cooling characteristics do not generally follow those of sea level engines and may be more critical. The installer may find it necessary to refine or improve existing installations to achieve satisfactory cooling. Critical cooling altitude may increase and it is possible that cooling may become critical in cruise on tightly cowled or clean engine installations. High altitude "hot day" takeoffs may also be critical. Installation cooling investigations should explore enough of the flight regime to ensure that the engine is adequately cooled and meets the engine manufacturer's requirements. The increased power and heat rejection of the turbocharged engine results in greater fuel demands under conditions of lower ambient pressure. The average sea level engine also obtains some fuel cooling by virtue of the manufacturer's recommendations to operate full rich above 75 percent power. It is also necessary to investigate the effects of a fuel leaning procedure at all cruise powers.

(3) The fuel system vapor lock characteristics may become more critical at altitude with high fuel temperatures. The freedom of the airplane fuel system from vapor lock should be substantiated.

(4) Installation of a fuel flowmeter in the engine supply line could cause vapor formation. The installation should be evaluated under hot weather conditions.

(5) Turbocharging the intake system of a carburetor system results in a combustible mixture that is pressurized at elevated temperatures. This combustible mixture should not be allowed to leak into the engine compartment.

(6) The use of a diaphragm type fuel pump has not been found to be adequate to supply fuel flow to the engine under all operating conditions. Therefore, it may be necessary to add a fuel boost pump and/or change the pumping system so that vapor does not develop in the fuel lines during normal operating conditions.

(7) The operating characteristics of the engine may be adversely affected and the restart characteristics should be evaluated.

(8) If an intercooler is installed:

(i) The mounting provisions of the cooler should be adequate to withstand the loads imposed on the system.

(ii) Air flow through the cooler should not discharge directly on the airplane windshield which could exceed the windshield temperature limit or cause any other failure.

(iii) Any changes to engine power, cooling characteristics, operating limits, and procedures should be evaluated.

(iv) Cooling air ducting should meet fireproof standards if a duct or shroud bypasses the cowling or firewall.

(9) Since there is a change in the engine power to altitude relationship, and also in the case of providing an increased power rating, the propeller/engine dynamics should be evaluated to determine if propeller recertification is necessary.

6. ACCEPTABLE MEANS OF COMPLIANCE.

a. The engine should be approved as part of the Engine Type Certificate or a Supplemental Type Certificate; however, compliance with § 23.909(a) will allow approval of the turbocharger system as part of the airplane. Approvals of engine and installation may be accomplished simultaneously. AC 33-2A contains information for obtaining type certification of engines. The following items should be considered during the engine approval:

(1) The engine modifier should provide or make available such instructions or manuals as are necessary for the installation, operation, servicing, maintenance, repair including welding limitations, rotor dynamic balancing and overhaul of the turbocharger and related installation parts, as required by §§ 33.4 and 33.5. Applicable manuals prepared by the manufacturer of turbochargers or other components may be utilized. Supplements to existing engine or airplane manufacturer's instructions should be provided if these instructions are made inadequate or inappropriate by the installation of the turbocharger. Specific attention is to be given to the possibility of component life limitations for both the engine and turbocharger.

(2) Any external lines or fittings carrying flammable fluid added as part of the turbocharger should be fire resistant as required by § 33.17.

(3) The ability of the turbocharger compressor and rotor case to contain damage resulting from rotor blade failure should be established, as required by §§ 33.19 and 33.27. Otherwise, shielding to contain escaping fragments should be

provided. Use of a compressor map to substantiate normal operation within allowable rotor speed limits is acceptable for initial theoretical design point; nevertheless, it should be verified in the actual aircraft installation during flight test.

(4) The effect of the installation of the turbocharger on the ice accretion characteristics of the induction system should be established as required by § 33.35(b). The relationship between the location of the turbocharger and point of fuel addition to the induction air should be considered. Temperature rise due to supercharger compression and conduction within the passage may be considered in establishing induction air heat requirements. When the fuel is added in the carburetor, a combustible fuel/air mixture under pressure and high temperature is available and requires special precautions.

(5) Adequacy of the induction system to withstand pressure differentials, both positive and negative, and temperature imposed by the turbocharger under the most critical condition should be established. Provisions to prevent drains from discharging hazardous quantities of fuel or fuel air mixture during engine operation should be provided (reference § 33.35). However, induction system drains are necessary to prevent fuel accumulating in the induction system and causing hydraulic lock of the engine. If a filter is installed in the induction system, an alternate air source is required. Combustible mixtures in the induction system may produce fire in the induction system due to backfire.

(6) Turbocharger oil inlet and outlet temperature and pressure limits necessary for satisfactory operation of the turbocharger should be established (reference § 33.30). If lubricated by the engine oil system, the capacity of the engine pressure and scavenge oil system should be adequate to lubricate and scavenge the engine and turbocharger under the most adverse conditions of oil temperature and bearing clearances. The ability of the engine breather system to handle any air entrained in the turbocharger scavenge oil without loss of engine oil or excessive pressure in the crankcase should be established. The oil consumption of this engine and turbocharger combination under the most adverse conditions should be established. Also, it may be necessary to determine that oil discharge temperature and pressure are within acceptable limits. Acceptable fuel/oil ratio should be checked to determine compliance with § 23.1011(b), as outlined in AC 23.1011-1. A turbocharger failure mode analysis should be made to ascertain that no engine oil loss and/or consequential failure may be probable.

(7) A turbocharger that pressurizes an airplane cabin should be investigated to substantiate that contamination of cabin air will not occur. Any contamination of cabin air from a failure of any component(s) of the turbocharger system should be avoided.

(8) If self contained, the capacity of the oil system should be adequate to provide lubrication at the most adverse conditions of oil temperature and turbocharger bearing clearance. Venting of the oil system should not permit excessive loss of oil. The oil consumption of the turbocharger should be established under the most adverse conditions. An acceptable fuel/oil ratio should be determined as required by paragraph (6) above.

(9) <u>Temperature limits</u> should be specified on any components requiring special cooling as required by § 33.21.

(10) <u>Turbocharger and engine mounting provisions</u> should have sufficient strength to withstand loads arising from the loading conditions prescribed in § 33.23.

(11) <u>Basic service life limits on the turbocharger rotor</u> should consider the effects of low cycle fatigue on rotor integrity and durability. A rotor without previous service history should be subjected to a 1000 cycle start-stop test under the most severe extremes of operation to provide a basis for establishing the initial service life.

(12) <u>Turbocharger control devices</u> should be designed such that any failure does not result in engine or turbocharger limits being exceeded. It is recommended that a pressure relief valve be provided as a safety device, as necessary, within the induction system to prevent overboosting of the engine.

(13) <u>Calibration tests and investigations</u> should be conducted to establish the sea level and altitude power characteristics of the engine and turbocharger combination when operated in accordance with the installer's instructions and proposed limitations for the combination, as required by §§ 33.45, 33.47, 33.49, 33.51, and 33.53 in conjunction with design analysis. Critical operating conditions and limitations for the power section and turbocharger should be established on the basis of these tests. The necessary instrumentation to monitor these conditions and limitations should be determined and specified as part of the airplane equipment list.

(14) <u>Testing as necessary</u> should be conducted to establish that the engine operates throughout its anticipated operating range without significant change in the basic engine detonation margin on the minimum grade fuel and fuel flow. Also, the limitations specified in the installer's instructions and as required by § 33.47 should be considered.

(15) <u>To determine that detonation limits established for the engine</u> are not exceeded in flight, it is recommended that detonation tests be evaluated in flight at various power, temperature, and fuel flow limits to establish the minimum fuel flow required for proper operation. Temperature monitoring should include induction air, cylinder head, and exhaust gas.

(16) <u>Endurance tests or investigations</u> should be conducted as necessary to meet the reliability standards established by the 150-hour endurance test under § 33.49, for the engine turbocharger combination including all essential components when operated in accordance with existing or proposed limitations and instructions. Service life of the components of the propulsion system should be established on the basis of the results obtained as required by § 33.7.

(17) <u>Any component of the engine and turbocharger installation</u> not substantiated as capable of operating in all normally anticipated flight and atmospheric conditions by endurance testing should be subjected to such additional tests or investigations as necessary to substantiate this capability as required by § 33.53.

(18) For those airplanes requiring compliance with the performance requirements of § 23.45, amendment 23-21, the actual calibrated power available at all altitudes should be established.

(19) If an intercooler is installed as part of the engine approval, the following additional considerations should be evaluated:

(i) The strength of the intercooler and mounting provisions should be evaluated as required by § 33.23.

(ii) The effects the intercooler has on the engine approved limits. Any additional instrumentation required should be specified so the engine does not exceed approved limits.

(iii) With an engine conforming to type design data, determine that the approved power is not exceeded at any altitudes. Establish manifold pressure, RPM, etc., limits to ensure operation within approved power limits.

(iv) To determine if propeller blade and crankshaft and propshaft stresses are within acceptable limits.

(v) Any ducting which bypasses the firewall and/or cowling should conform to fireproof requirements.

b. The installation of a turbocharged engine should be approved as part of the airplane type certificate or supplemental type certificate and should consider the following items:

(1) The design of turbocharger mounts and their supporting structure should withstand all vibration and inertia loads to which they are subjected in operation as required by § 23.307. The strength of the materials used should consider the effect of the maximum temperatures to which they are subjected under the most adverse conditions by the turbocharger installation. The three axis vibratory excitation limits of the turbocharger mounting should be considered on the ground and in-flight.

(2) The fuel system should be free from vapor lock at the increased engine fuel demands throughout the flight envelope as required by § 23.961. Engine in-flight restart procedures should be evaluated and demonstrated.

(3) The powerplant cooling provisions should be capable of maintaining the temperatures of all powerplant components, engine parts, turbocharger parts and fluids at or below the maximum established safe values under all ground and flight operating conditions as required by §§ 23.1043 and 23.1047.

(4) The induction system should meet the requirements of § 23.1091 and incorporate means to prevent and eliminate ice accumulations within the engine and turbocharger induction system as required by § 23.1093. The heat rise requirements of § 23.1093(c) should be evaluated. Service experience indicates that abnormally high induction air temperature adversely affects the engine's

overhaul life. Induction system drains may be necessary to carry any accumulated fuel and water overboard. Alternate air is required to allow for the possibility of filter blockage. Magnetic latches in the duct system are to be avoided; manually operated control of the alternate air system is preferred. The source of alternate air should be in a sheltered location; however, if the air source is to be used for cabin pressurization, the location cannot pick up contaminated air.

(5) All portions of the engine exhaust system and turbocharger should be isolated from lines or components carrying flammable fluids, the accessory section, and primary structure by suitable firewalls, shrouds, or by an adequate distance of separation as required by § 23.1121. Where required, adequate cooling air should be provided so that there is no adverse change in service life or failure rate of adjacent components.

(6) The exhaust system and its supports should be capable of withstanding all vibration and inertia loads at the higher temperature and pressures they are subjected by the turbocharger installation as required by § 23.1123. Provisions for expansion and flexibility should be provided between the exhaust conduits and the turbocharger. Flexible joints in the exhaust system should not permit the leakage of hazardous quantities of exhaust gases, or the impingement of hot exhaust gases on lines carrying flammable fluids or on primary structure. Tests or investigations as necessary should be conducted to substantiate the exhaust system meets the standards of airworthiness established by the basic engine 150-hour endurance test as required by § 33.49. The results should also be integrated into the determination of inspection and overhaul time periods.

(7) Necessary instrumentation should be provided to establish engine or turbocharger limits such as manifold pressure, induction/carburetor inlet temperature, turbocharger oil pressure, temperature and exhaust gas pressure, and material temperature are not exceeded. Establish with test equipment that turbocharger maximum speed will not be exceeded during all intended operating conditions.

(8) Since additional moisture may be introduced into the engine crankcase, it is important that extra protection of the engine crankcase breather be provided to prevent blockage by ice.

(9) The Airplane Flight Manual (AFM) and applicable placards should be revised to define all operating limitations or instructions.

(10) If performance information is required per § 23.45, amendment 23-21, the actual engine power at altitude should be determined.

(11) If turbocharger is used to pressurize the cabin, contamination of the cabin should be evaluated.

(12) If an intercooler is installed, the following additional considerations should be evaluated:

(i) The strength of the intercooler and mounting provisions should be evaluated as required by §§ 23.307 and 23.361. Vibration of the intercooler and lines should also be considered.

(ii) To ensure proper (original) efficiency of the unit, the intercooler should not be painted.

(iii) A shake test should be conducted on the intercooler so that failed internal cooling fins may not be detached and ingested by the engine.

(iv) Engine cooling tests should be reevaluated with the intercooler installation, as required by §§ 23.1043 and 23.1047.

(v) Any additional instrumentation required for the intercooler should be provided to ensure that the engine ratings are not exceeded (see paragraph 5a(13).

(vi) Any cowling or airframe protrusions located in front of the firewall should be constructed from fire resistant material except if these protrusions form a part of the firewall, they should be constructed from fireproof material. Air exit ducts should not permit impingement of gases on the windshield in the event of an engine compartment fire.

(vii) Maintenance procedures should contain a caution to shield the intercooler during painting to prevent paint accumulation restricting or limiting cooling air flow.

(13) The propeller-engine-airplane vibration and engine crankshaft torsion characteristics should be reevaluated at altitude to provide continued compliance with § 23.907.

(14) If a cabin heater system is used in conjunction with the engine turbocharger system, then windshield defogging capability should be demonstrated.

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